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# Simultaneous Consumables, Resources, and Spares Optimization for Future Combat System Logistics

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# Talk Overview

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- Motivation
- The System-of-Systems Analysis Toolkit (SoSAT)
- Hybrid Simulation and Optimization Strategies
- Randomized Greedy Search
  - Generating Solutions for Individual Scenarios
- Progressive Hedging
  - Aggregating Solutions Across Multiple Scenarios
- Conclusions
- In-Progress and Future Research Directions



# Motivation

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- Logistics optimization in the context of Future Combat Systems poses many difficult challenges for the algorithm designer
  - Same goes for SBCT, HBCT, IBCT, ...
- Feature #1: Simultaneous consideration of spares, resources, and commodities
  - Aspects are typically treated independently, and combined *a posteriori*
  - Yields sub-optimal solutions due to lack of separability
  - Yields infeasible solutions due to log footprint constraints
- Feature #2: Short time-scales
  - Ground combat operations are a transient phenomenon
  - Day to week-long missions = > marginal analysis solutions are unstable
- Feature #3: Non-parametric failure distributions
  - Damage incurred due to force-on-force action is non-parametric
  - Extant logistics optimization algorithms assume parametric distributions

# SoSAT: The System-of-Systems Analysis Toolkit (1)





# SoSAT: The System-of-Systems Analysis Toolkit (2)

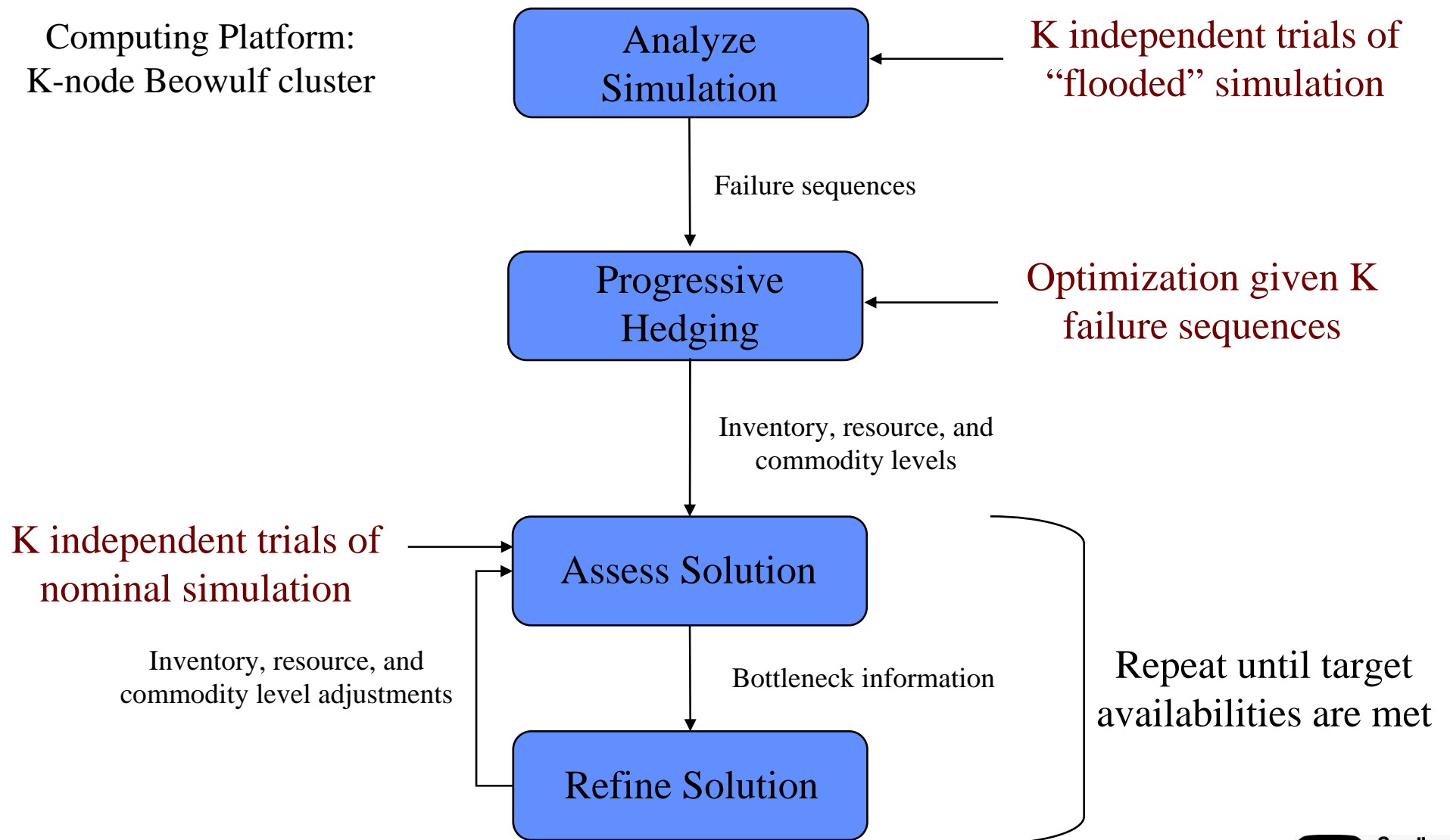
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- Observation
  - Logistics solutions are increasingly being developed in the context of simulation, as opposed to analytic, models
- Sandia's SoSAT tool for Future Combat System logistics modeling
  - Time-stepped, PC-based, high-resolution logistics simulator
- What operations can SoSAT model?
  - Logistics / reliability for brigade-level ground combat systems
    - FBCT, SBCT, HBCT, IBCT
    - Thousands of platforms, each with tens to hundreds of parts
  - 15 minute time-steps
  - Stochastic models of combat damage via CASTFOREM runs
  - Dynamic business rules, platform inter-dependencies
- What analytic capabilities does SoSAT provide?
  - Tracks operational availability, lethality, mobility, etc., over time
    - On platform/squad/platoon/etc. levels
  - Quantifies variability and related statistics over N trials
  - “What-if” assessment of structure / platform modifications



# Integrating Simulation and Optimization Models

Computing Platform:  
K-node Beowulf cluster

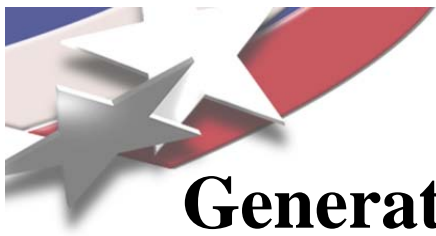




# Generating Solutions for Individual Scenarios (1)

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- Output from a *single* flooded simulation run yields
  - Failure sequence for each part on each platform
  - “Run-out” times for each commodity on each platform
- Analysis of simulation model yields
  - Impact of not having a spare part, commodity, or resource
  - E.g., lack of a tread downs M1A2 mobility and availability
- Optimization objective
  - Determine a “minimal-cost” solution that will achieve target performance metrics (e.g., 95% availability) given a *particular* failure sequence
- Observations
  - Approach assumes independence of failures => solution is conservative
    - E.g., lack of a tread on day N might delay engine failure on day N+2
  - Aggressive performance targets => conservatism is not significant
    - E.g., delays are not long given requirement of 95% availability
  - Assumes prescience; solution does not generalize!



## Generating Solutions for Individual Scenarios (2)

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- Short time horizons facilitate very high-speed simulation
  - Few numbers of failures during training missions
  - Moderate number of failures during combat missions
- Developed a discrete-event “surrogate” of SoSAT
  - Input: Failure sequence under flooded SoSAT simulation
  - Input: Proposed spares, resource, and commodity levels
  - Output: Performance metrics for the provided solution given the particular failure sequence (i.e., scenario)
  - Execution time: Milliseconds
- Domain-specific heuristics are used to obtain an initial solution
  - Highly sub-optimal, typically infeasible
- “Marginal analysis” is used to iteratively adjust spares / resource / commodity levels
  - ROI is quantified (exactly) using the surrogate simulator
  - Executed until feasibility w.r.t. footprint and performance is achieved
- Optimality gap has been assessed off-line using a Mixed-Integer Program
  - Within *at worst* 5% of optimality, more likely 1-2%



# The Single-Scenario Solution Approach: Discussion

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- This approach is a dramatic shift from traditional marginal analysis
  - Why bother?
- Offers several advantages over marginal analysis and other approaches
  - Paradigm simplification; focus is on individual scenarios
  - Natural to simultaneously consider spares, resources, and commodities
  - Non-parametric; can handle any form of failure type
  - Far easier to impose business rules and side constraints
  - Meet performance targets – not just “in expectation”
  - Expression and satisfaction of complex performance metrics
- But with the baggage of
  - Increased computational costs (more later)
  - Exact solutions, restrictive assumptions => heuristic solutions, few assumptions
  - Far less developed problem domain theory



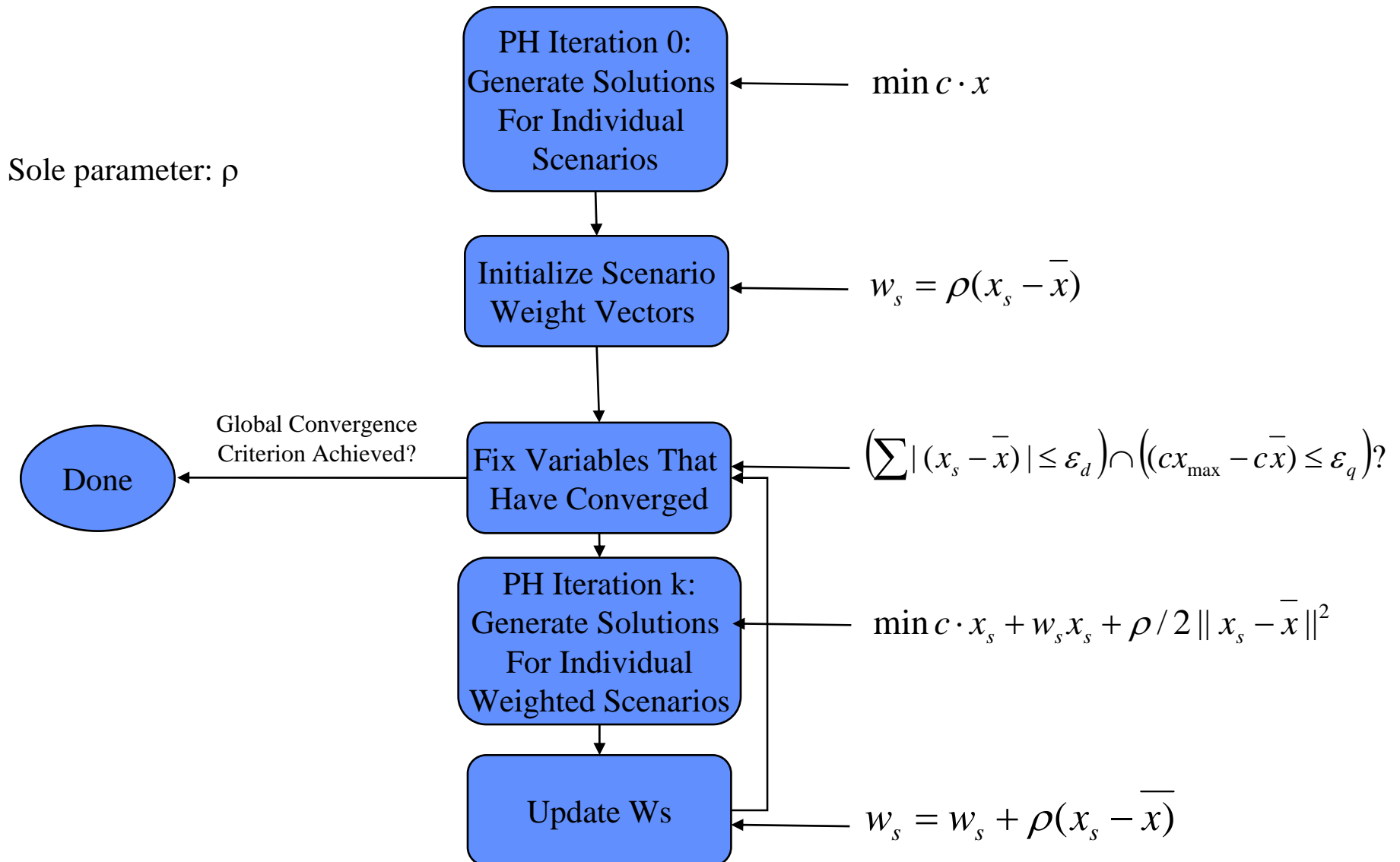
# Progressive Hedging: Overview

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- We now have solutions to  $N$  independent scenarios
  - So what? We aren't prescient...
- The next stage is intelligent solution blending
  - No individual solution yields good performance in all scenarios
  - Taking the “maximum” solution yields infeasibilities, unacceptable cost
- An effective alternative: Progressive Hedging (PH)
  - A “horizontal” scenario decomposition technique
    - Stochastic (mixed-integer) programming
    - Contrast with “vertical” or stage-based decomposition techniques
    - Rockafellar and Wets (1991)
  - In general, multi-stage (decision making with recourse)
    - Not used yet, but an interesting future avenue
- General observation
  - Logistics optimization problems can be canonically expressed as Stochastic Mixed-Integer Programs



# Progressive Hedging: High-Level Architecture





# Progressive Hedging: Discussion

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- Convergence proofs for PH
  - Global optimum in the case of convex problems (SLP)
  - Local optimum in the case of non-convex problems (SMIP)
- Selection of “good” values for the  $\rho$  parameter is an art
  - Magnitude dictates convergence speed
  - Intuitively should be cost-proportional
  - Mathematically-motivated heuristics (Watson, Woodruff, and Strip)
  - Goal is to trade off optimality for convergence speed
- Other algorithmic engineering techniques
  - Fix lags (fix variables if they have stabilized over last N iterations)
  - Cycle detection and cycle breaking
  - Acceleration once termination criteria is “nearly” achieved
- Progressive Hedging is trivially and efficiently parallelized
  - Individual scenario solves are independent
  - Barrier synchronizations to compute/update weights and solution statistics



# Progressive Hedging: Results

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- Unclassified, real-world-inspired test problem
  - 100 platforms, 50 parts per platform
  - One-week surge
  - 30 scenarios
- Optimization objective
  - 95% operational availability in all scenarios
  - All scenarios are feasible
- Solution obtained via PH in ~500 aggregate minutes of run-time
  - Parallelization on Beowulf cluster yields 25 minutes wall-clock time
  - Within 5% of optimality (determined via expensive MIP solves)
- Scalability to FCS-sized problems is under way
  - Understanding algorithm behavior as a function of proportion of spares, resources, and consumables levels



# Conclusions

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- Logistics optimization for the Future Combat System raises several key and novel algorithmic challenges
  - Simultaneous spares, resources, and commodities
  - Non-parametric analysis
  - Short time horizons
- Simulation-based optimization can be leveraged to yield solutions to individual mission scenarios
- Progressive hedging can effectively blend individual solutions into a consistent global solution
- New approach offers advantages over traditional logistics optimization approaches, but simultaneously incurs unique costs
- Much work remains in this area
  - Potential to ignite novel, interesting algorithmic work



# In-Progress and Future Research Directions

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- “Outlier-Aware” optimization
  - Empirically, there are many scenarios for which feasible solutions are extremely expensive
  - New design objective: Generate the minimal-cost logistics solution that satisfies the performance targets in 95% of the mission scenarios
- Robust optimization
  - To what solution components is performance most sensitive?
  - How can generate less sensitive solutions?
  - What is the trade-off between cost and robustness?
- Run-time reductions in Progressive Hedging
  - Even better  $\rho$  selection methods
  - Improved convergence accelerators



# Questions?

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- Thanks!
- Progressive Hedging Innovations for a Stochastic Spare Parts Support Enterprise Problem (Watson, Woodruff, Strip)
  - *Submitted*